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ACCURACIES OF
RADIOSONDE DATA

SEPTEMBER 1955

HEADQUARTERS
AIR WEATHER SERVICE
MILITARY AIR TRANSPORT SERVICE
UNITED STATES AIR FORCE
WASHINGTON 25, D.C.

AWS TECHNICAL REPORT)
NO. 105-133   )

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FOREWORD

1. __Purpose.__ AWS Technical Report 105-133, "Accuracies of Radiosonde Data" is published for the information of all weather personnel concerned with analysis, forecasting, or climatological work, using upper air data obtained by radiosondes. It will provide them with indications as to the probable accuracy of radiosonde observations from equipment of the U. S. meteorological services.

2. __Scope.__ This Report summarizes the best available information on the errors of the radiosondes in current use in U. S., for temperature, pressure, humidity, and height. An elementary discussion of the statistical terms and concepts used for expressing the accuracy or error is also included.

3. __Additional Copies.__ This Technical Report is stocked at Headquarters, MATS, AG/Publications. Additional copies may be requisitioned from Headquarters Air Weather Service, ATTN: AWSAD, in accordance with AWS Regulation 5-3, as amended.

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ACCURACIES OF RADIOSONDE DATA

I. INTRODUCTION

The question of radiosonde accuracies is one which is often asked but seldom answered to complete satisfaction. While the reasons for this are many and complex, the basic difficulty lies in the fact that there is no method by which the absolute accuracy of data from a radiosonde can be directly determined once the instrument leaves the ground.

Instruments for measuring meteorological elements on or near the ground may be compared with precision instruments of known accuracy and the accuracy of measurement thereby determined. Radiosondes are also checked in this manner. Unfortunately, however, the mass of data obtained over a period of years from radiosondes shows rather conclusively that accuracies under such conditions are not maintained in actual flight. The users of upper air data, nevertheless, have a continuing need for infor- mation on the accuracy they can expect from in-flight data; and various studies, re- ports, investigations, and analyses of observational data have been made in an attempt to provide this information. As might be expected the results of these investigations are not in complete agreement; one will find estimates of the "error" in temperature, for example, from a few tenths of a degree to as much as one, two, or even three degrees. One reason for this variation is that the concept of accuracy has been de- fined by the several investigators in different ways. It is the purpose of this paper to discuss the definitions of "accuracy" and to compare and evaluate the results of available studies and reports on accuracies of radiosonde data. These results will provide information to forecasters, analyists, and other users of upper-air data which may be used in determining the limits within which data available to them are valid.

II. STATISTICAL MEASURES FOR INDICATING ACCURACY

As stated above, the "accuracy" ascribed to any measuring instrument may be mis- leading because of the numerous ways of estimating and expressing accuracy. It is customary to use various statistical measures of dispersion to indicate accuracy and those most often used are the standard deviation, the average deviation, and the prob- able error.

These measures of accuracy can best be illustrated by use of the "normal probabil- ity curve." This curve assumes that the frequency of occurrence of the errors (ver- tical axis) grouped according to magnitude (horizontal axis) will show a symmetrical distribution, high in the center and tapering toward zero in either direction. (Figure 1)

The "true" value (zero error) of the element being measured is represented by "0" in Figure 1. Since this value cannot be determined by direct measurement, the assumption is made that the "true" value is equal to the arithmetic mean (or average) of the observations. The area under the curve bounded by the lines on either side of "0" represents the dispersion or spread of measurements which deviate from the true value. For example, 68.27% of the measurements will fall between the vertical lines labeled ±1; 95.45% between ±2; and 99.73% between ±3. In a normal distribution these distances from the mean represent 1, 2, or 3 standard deviations. The assumption that radiosonde errors are normally distributed is generally considered valid. Refer- ence $\underline{/3\underline{/}}$ contains a complete discussion of the validity of this assumption.
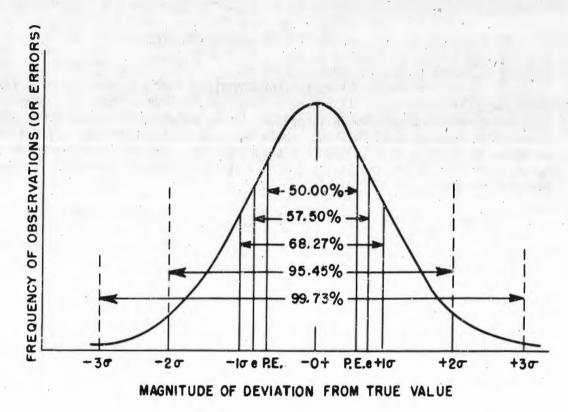
Fig. 1. Normal Probability Curve, Showing Ordinates and Abscissae for 1σ, 2σ, 3σ, P.E., and Average Deviation (e)

1. <u>Standard Deviation</u>. The standard deviation, then, is a measure of the spread or distribution of data above and below the "true value" and can be stated mathematically as follows:

$$\sigma = \sqrt{\frac{\sum x^2}{N}},$$ where σ is the standard deviation (or

root mean square), $\sum x^2$ is the sum of the squares of the deviations from the mean, N is the number observations. If the distribution is <u>normal</u>, i.e., has a symmetrical bell-shaped frequency curve as shown in Figure 1, 68.27% of the errors will be less than 1σ and 31.73% of the errors will have an absolute value equal to or greater than 1σ. It can also be seen that the odds against any measurement having an error equal to or greater than 1σ are 2.15 to 1. Similar figures for multiples of 1 are given below:

TABLE 1

K	Percent of deviations less than $K\sigma$	Odds against a deviation greater than $K\sigma$
1	68.27%	2.15 to 1
2	95.45	20.98 to 1
3	99.73	369.4 to 1
4	99.99366	15,772 to 1
5	~100	1,744,000 to 1
6	~100	5.0×10^8 to 1
7	~100	3.9×10^{11} to 1

2. <u>Average (or Mean) Deviation</u>. The average deviation is determined as follows:

$$e = \frac{\Sigma |x|}{N}, \text{ where e is the average deviation,}$$

$\Sigma |x|$ is the sum of the absolute values of the deviations, and N is the number of deviations. If the distribution is normal (Figure 1), 57.5% of the deviations are included between the mean and $\pm$e. The average deviation is related to the standard deviation by $e = 0.8\sigma$.

3. <u>Probable Error</u>. The probable error is the value which will be exceeded in 50% of the observations. In a normal distribution, the probable error is related to the standard deviation by P.E. $= 0.67\sigma$.

4. <u>"Maximum Error"</u>. As noted in Figure 1, there is no limit to how far the measurements can vary from the mean (the bell-shaped curve approaches the horizontal axis asymptotically). In practice, however, if the standard deviation is known, then we may assume that practically all observations will fall within a range of 3σ of the mean (theoretically, this range includes 99.7% of the observations). The "maximum error," then, is usually considered to be about 3σ .

5. In summary we have the following relationships among the various measures of dispersion in a normal distribution: Standard Deviation $= \sigma$; Probable Error $= 0.67\sigma$; Average Deviation $= 0.80\sigma$;"Maximum Error" $= 3\sigma$.

6. In the following discussion the above relationships will be used to convert the various measures of accuracy stated in reports, studies, etc., to the <u>standard deviation</u>. Statements or estimates of accuracy can then be compared and evaluated. For a complete discussion of the normal distribution curve and the measures of dispersion mentioned above, reference should be made to the "Handbook of Statistical Methods in Meteorology," Publication M.O. 538 (British Meteorological Office, 1953 or other standard text on statistical methods.

III. TEMPERATURE MEASUREMENT ERRORS

1. <u>Sources of Errors</u>. There are, of course, numerous sources of error which contribute to the final temperature data obtained from radiosonde observations. Most of these sources and the possible magnitude of the error contributed by each are listed below (taken from $\boxed{2}$).

TABLE 2

Source of Error	Maximum Error (3σ) $^\circ$C	σ $^\circ$C
Thermistors.	$\pm$0.5	$\pm$0.17
Manufacturer's standard thermometers	$\pm$0.1	$\pm$0.03
Transmitter measuring circuit.	$\pm$0.5	$\pm$0.17
Ground Equipment stability	$\pm$0.5	$\pm$0.17
Readability of recorder chart (0.2 divisions)	$\pm$0.5	$\pm$0.17
Baseline check (thermometer plus readings) .	$\pm$0.4	$\pm$0.13
Evaluator readability.	$\pm$0.1	$\pm$0.03

3

An estimate of the total standard deviation can be obtained (assuming that these errors are independent and normally distributed) by taking the square root of the sum of the squares of the individual standard deviations. On the basis of this assumption, a total standard deviation of ±0.36°C is obtained. While this value is not representative of the temperature accuracies obtained operationally, it falls very close to values obtained under flight similitude tests on radiosondes. The inability of any radiosonde to measure temperature as accurately in flight as it does on the ground under controlled conditions is well known. Just how much the performance of the radiosonde in flight differs from its performance in laboratory tests may be estimated from the following review of the limited number of reliable reports, studies, etc., available on this subject.

2. Study by New York University. Reference [3] describes a study conducted by the New York University under a Signal Corps contract on the "Effect of Variability and Instrumental Error on Measurements in the Free Atmosphere." For a series of flights (approx. 9) two radiosondes were attached to each balloon and tracked independently by two AN/GMD-1's. The study assumed that the errors of temperature were distributed according to the normal curve (Figure 1). The variance (σ^2) of the error was computed for standard pressure levels. The standard deviation, therefore, is obtained by taking the square root of the error variance. The standard deviations thus obtained are listed in Table 3.

TABLE 3

Mb	σ °C
850	±0.70
700	±0.65
500	±0.97
400	±1.3
300	±1.2

3. Radiosonde Compatibility Tests at Oklahoma City. In June 1951, a radiosonde compatibility test was conducted at Oklahoma City, Oklahoma. In this test 3 to 4 radiosondes used by the U. S. meteorological services were flown on one train. Over 30 ascents were made in which the types of radiosondes in the train were varied so that each instrument would be compared with all other instruments and with another instrument of its own type. The report of these tests is contained in [2], and the results with respect to temperature data are summarized in Table 4.

TABLE 4

Results Obtained at Oklahoma City

For all constant pressure surfaces from surface through 400 mb:

61% agreed within 1°C

91% agreed within 2°C

98% agreed within 3°C

(2% departed by more than 3°C)

From 300 mb through 100 mb:

56% agreed within 1°C

83% agreed within 2°C

94% agreed within 3°C

97% agreed within 4°C

(3% departed by more than 4°C)

It is realized that the data obtained from these tests indicate differences in the various radiosondes rather than absolute accuracies. Nevertheless, if we assume the data from these tests were normally distributed, standard deviations can be computed. These computations show a standard deviation of 0.82°C from the surface to 400 mb, and 0.99°C from 300-100 mb.

4. "Compendium of Meteorology" [8] Article. In the Compendium of Meteorology [8], Dr. M. Ference, formerly of the Signal Corps, states that "the over-all probable error in temperature measurement is about +0.5°C. The same value is stated in SCEL Technical Memo No. M-1341, "Study on Single Station Atmospheric Sounding System" [1]. According to Section II above, this is equivalent to a standard deviation of +0.74°C.

5. Minimum Performance Characteristics of ACC/MET. The Air Coordinating Committee, Sub-Committee on Aviation Meteorology, has established certain "minimum performance characteristics" for radiosondes, including recommended temperature accuracies, as follows:

+1.5°C from +40°C to -50°C

+2.0°C from -50°C to -70°C

+3.0°C from -70°C to -90°C

These values were recommended by ACC/MET as representing reasonable accuracies to be expected of the temperature data obtained from the radiosondes used by the various U. S. meteorological services. While the recommended values are somewhat arbitrary, they were nevertheless carefully chosen on the basis of individual evaluations, tests, and close association with radiosonde data by personnel of the meteorological services. The fact that they agree rather closely with results obtained from experimental data, therefore, is not coincidental. It is reasonable to assume that these figures encompass at least 95% of all observations and would be equivalent to approximately 2 standard deviations. The respective standard deviations, therefore, would be +0.75, +1.0, and +1.5°C.

6. <u>Summary</u>. From the sources cited above it can be seen that estimates of upper-air temperature errors stated as standard deviations range from ±0.65°C to ±1.5°C. These estimates are summarized in Table 5.

TABLE 5

Source	σ (range) °C
1. NYU Report	0.65 to 1.3
2. Oklahoma City Tests	0.82 to 0.99
3. ACC/MET	0.75 to 1.5
4. Compendium of Meteorology	0.74
Average	0.74 to 1.26

7. <u>Conclusions</u>. It has become the practice in recent years to assume a value of ±1°C for the standard deviation of the errors or root mean square error (sometimes referred to as "standard error")* of upper-air temperature data (see [4], [5], [6], and [7]). Admittedly, this is a convenient figure for computational purposes. From the estimates outlined above it is also a valid figure, at least for altitudes up to roughly 50,000 to 60,000 feet. At higher altitudes the absolute error may increase somewhat; in the lower levels it may be somewhat smaller. In certain cases the accuracy of temperature <u>differences</u> (change of temperature with height) is more important than the accuracy of absolute values. This accuracy remains well within ±1°C since the incremental error is less than the absolute error (see [4]).

IV. PRESSURE AND HUMIDITY MEASUREMENT ERRORS

1. <u>Pressure-Measurement Errors</u>. Flight similitude tests on radiosondes show that the pressure accuracies fall well within the maximum tolerances allowed. These tolerances are listed in Table 6 [2].

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* Strictly speaking the "standard error" is a special case of the standard deviation, the standard deviation of a sampling distribution which is perfectly normal or nearly so, and hence is better known as the "standard error of estimate." In some British books the term "standard error" is loosely used as a synonym for any standard deviation, a practice which is not generally condoned by statisticians.

TABLE 6

Source of Error	Error (mb)			
	Sfc to 50,000 ft.		Above 50,000 ft.	
	3σ	σ	3σ	σ
Error of Standard Barometer	±0.3	±0.1	±0.3	±0.1
Error of Operating Standard Barometer	±0.5	±0.17	±0.5	±0.17
Accuracy of Pressure Element	±4.0	±1.3	±2.0	±0.67
Temperature Effect	±4.0	±1.3	±2.0	±0.67
Station Barometer	±1.0	±0.3	±1.0	±0.3
Error in Estimating Fractional Contacts	±3.0	±1.0	±1.0	±0.3

From Table 6 the total standard deviation is found to be approximately ±2.12 mb from the surface to 50,000 feet and ±1.06 mb above 50,000 feet.

The ACC/MET minimum performance requirement is stated as ±8.0 mb from 1050 mb to 40 mb (approximately 74,000 feet). This represents a standard deviation of approximately ±4.0 mb.

Studies of the accuracy of pressure data obtained from the AN/GMD-1A system have been conducted by the Signal Corps. Their studies show the data to have an average error of ±3 mb below 50,000 feet with indications of improved accuracy at higher altitudes [1]. This represents a standard deviation of 3.75 mb below 50,000 feet and a smaller value above 50,000 feet. An acceptable value for the standard deviation of pressure errors up to at least 50,000 feet is ±3 mb [4] [5]. It will be shown in Section V, para. 1 below, that pressure errors contribute very little to the error in computing the height of constant-pressure surfaces up to the 10-mb surface. The value of ±3 mb will be assumed for all altitudes, therefore, in discussing such errors. Smaller values of pressure errors at high altitudes, however, will be assumed in discussing the errors involved in determining the true height of the radiosonde (see Section V, para. 2 below).

2. Humidity Measurement Errors. It is well known that the accuracy of humidity data from upper-air soundings leaves much to be desired. Under ideal conditions the standard deviation of humidity errors is estimated to be approximately ±5%. At temperatures above 0°C this accuracy may be achieved in the field provided the humidity element is not exposed to high humidities (95 to 100%) and particularly if the instrument has not passed through clouds or precipitation. At low temperatures the above limitations plus the high lag characteristics of the sensing element make it extremely difficult to state the expected accuracy of humidity data for any specific sounding. The lower operational limit of the present humidity element is about -40°C.

V. HEIGHT-DETERMINATION ERRORS

In discussing the accuracy of height data computed from upper-air soundings it is necessary to distinguish between the heights assigned to constant-pressure surfaces and the heights assigned to specific points on the temperature curve or to the height of the radiosonde [7]. While both heights are computed in the same manner, the

accuracies of the two heights are quite different. For example, the standard deviation of errors in computing the height of the 200-mb pressure surface is approximately 160 feet; in determining the height of the base of an inversion plotted at 200-mb, however, the standard deviation is more than twice this value. In other words, the height of a given pressure surface can be determined more accurately than the height of the radiosonde at the time it indicated this pressure. This distinction is important since the latter height is used in computing and coding wind data and in assigning heights to significant temperature levels (e.g., bases and tops of inversions, instability layers, 0°C isotherm, etc.). These two types of height errors are discussed below.

1. **Height of Pressure Surfaces.** Heights of constant-pressure surfaces are determined by a solution of the hydrostatic equation which defines the thickness between any two pressure surfaces. From the hydrostatic equation the error (Δ h) in determining the thickness between any two pressure surfaces is shown to be:

$$(1) \quad \Delta h = c \ln \frac{P_1}{P_2} \left(\overline{\Delta T} - \frac{\partial T}{\partial p} \overline{\Delta P} \right), \quad \text{where} \quad c = \text{a constant}, P_1 \text{ and } P_2 =$$

lower and upper boundary pressures, respectively, $\overline{\Delta T}$ = mean error in temperature (virtual), $\frac{\partial T}{\partial p}$ = baric lapse rate, (here assumed constant from P_1 to P_2),

$\overline{\Delta P}$ = mean error in pressure. It can be seen that the error in determining the thickness of a layer between two pressure surfaces is a result of:

    a. error in determining the mean virtual temperature of the layer and,

    b. mean error in the measurement of pressure.

The magnitude of the error due to pressure inaccuracies is a function of the baric lapse rate (change of temperature with pressure).

1.1 **Error in Thickness Due to Temperature Error.** The component of the thickness error due to the error in determining the mean virtual temperature is:

$$(2) \quad \Delta h_T = c \ln \frac{P_1}{P_2} \overline{\Delta T} . \quad \text{Using the value of 1°C for the standard}$$

deviation in temperature error ($\overline{\Delta T}$), the standard deviation in thickness error between various pressure surfaces can be computed from equation (2). These are shown in Table 7.

TABLE 7

Layer (mb)	Δh_T (ft)
1000-700	34
700-500	32
500-300	49
300-200	39
200-100	67
100-50	67
50-25	67
25-10	88

The standard deviation in the height error of each pressure surface can be obtained by adding the thickness errors; (the temperature error, ΔT, is assumed to maintain the same sign throughout the sounding):

TABLE 8

Height (mb)	σ_{hT} (ft)
700	34
500	66
300	115
200	154
100	221
50	288
25	355
10	443

1.2. Error in Thickness Due to Pressure Error. The component of the thickness error due to error in the measurement of pressure is:

$$(3) \quad \Delta h_p = -c \ln \frac{P_1}{P_2} \frac{\partial T}{\partial p} \overline{\Delta P}$$

It should be noted that the controlling factor in determining the thickness error due to pressure error is the baric lapse rate ($\partial T/\partial p$). If the temperature curve in the layer is isothermal, ($\partial T/\partial p = 0$) there is no error due to pressure in computing the thickness regardless of how large the error in pressure measurement (ΔP) may be. In addition, as the lapse rate changes sign (in the stratosphere, for example) thickness errors accrued in the troposphere will be partially cancelled. In other words, the pressure error in the radiosonde data plays a very minor role in determining the accuracy of the heights of constant-pressure surfaces, at least up to approximately 10 mb. This is shown in the following tables. Table 9 shows the thickness errors using $\Delta P = +3$ mb and $\partial T/\partial p$ based on a mean of 508 soundings between 9°N and 65°N $[4] [5]$. It is not a typical sounding for any season or latitude but serves to illustrate the effect of pressure errors on height computations $[4] [5]$.

TABLE 9

Layer (mb)	Δh_p (ft)
1000-700	- 4
700-500	- 8
500-300	- 19
300-200	- 16
200-100	- 14
100- 50	+ 18
50- 25	+ 48
25- 10	+103

9

In Section IV, paragraph 1 above, it was shown that a value of ± 3 mb is an acceptable standard deviation for pressure errors. Using this value and $\partial T/\partial p$ from the sample sounding, the height errors for each pressure surface are shown in Table 10. It should be noted that the errors computed for Tables 9 and 10 will be slightly different for different soundings. $\underline{/5\_7}$ These cannot strictly be regarded as standard values, since in practice $\partial T/\partial p$ will vary from sounding to sounding. However, the figures are indicative of the magnitude of errors to be expected in the height of the pressure surfaces due to errors in the measurement of pressure. We have assumed in this example that the error in the pressure measurement was ± 3 mb throughout the sounding. We see from Table 10 that this results in too low height values up to 50 mb, errors increasing up to the tropopause, and decreasing above due to the reversal of the sign of $\partial T/\partial p$. In the stratosphere the errors are gradually canceled and reach their lowest absolute value around 25 mb thence increasing with opposite signs. If the pressure error had been -3 mb, all the signs in Table 9 and 10 would be reversed.

TABLE 10

Height (mb)	σ_{hp} (ft)
700	- 4
500	- 12
300	- 31
200	- 47
100	- 61
50	- 43
25	$\neq$ 5
10	$\neq$108

    1.3. <u>Total Error in Height of Pressure Surfaces</u>. From the standard deviation of error in height of pressure surfaces due to temperature errors (σ_{hT}) and pressure errors (σ_{hp}) the total error (σ_h) due to both these factors can be computed. Assuming that σ_{hT} and σ_{hp} are independent the total error is given by:

$$(4) \quad \sigma_h = \sqrt{(\sigma_{hT})^2 + (\sigma_{hp})^2}$$

Table 11 shows this total error. Tables 8 and 10 are repeated for comparison.

TABLE 11

Height (mb)	σ_{hT}	σ_{hp}	σ_h
1000	0	0	0
700	34	4	34
500	66	12	67
300	115	31	119
200	154	47	161
100	221	61	229
50	288	43	291
25	355	5	355
10	443	108	456

2. **Height of the Radiosonde.** In the preceding paragraph it was shown that the standard deviation of the error in computing the height of a pressure surface, for example, the 200-mb surface, was 161 feet. It was also shown that this error was due primarily to the error in measuring temperature and only slightly to the error in measuring pressure. The pressure error, however, becomes of major importance in determining true height of the radiosonde instrument at the time it indicates a given pressure. For example, if the radiosonde indicated a pressure of 200 mb, the true position of the radiosonde would be above or below the computed height of the 200-mb surface by the equivalent of the pressure error expressed in feet. Since 1 mb at 200 mb is equivalent to approximately 105 feet, a 3-mb error would place the radiosonde approximately 315 feet above or below the calculated height of the 200-mb surface. In this example the total standard deviation of errors in true height would be the square root of the sum of the squares of 161 feet and 315 feet, or 354 feet. Table 12 shows the standard deviation of errors in true height of the radiosonde at various pressure levels, assuming a 1°C standard deviation of errors in temperature and a 3-mb standard deviation of errors in pressure up to and including 200 mb. Above 200 mb, however, smaller values of pressure error are assumed.

In Section IV, paragraph 1, it was stated that the accuracy of pressure measurement improved at altitudes above 50,000 feet. Since the total error in the height of pressure surfaces is affected only slightly by the error in pressure measurement, a value of ± 3 mb was used for all altitudes to compute σ_h in Table 11. It can be seen, however, from Table 12 that in computing errors in true height (σ_z), the pressure error plays the dominant part. It is necessary, therefore, to use the increased accuracy in pressure measurements above 50,000 feet for such computations. According to Table 6 the pressure errors at altitudes above 50,000 feet should be half as great as the error below 50,000 feet. Although little test data are available to establish an accuracy value at the higher altitudes, Reference [1] states that an accuracy of ± 1.5 mb is indicated. Table 12 shows the standard deviation in the error of true height based on a pressure error of ± 1.5 mb at pressures of 50, 25, and 10 mb. Since the accuracy of pressure measurement increases gradually rather than abruptly from ± 3.0 mb to ± 1.5 mb, a value of ± 2.0 mb was used at the 100-mb pressure level.

TABLE 12

Pressure (mb)	Error in Height of Pressure Surface (σ_h from Table 11)	Corresponding Pressure Error (in feet)*	Standard Deviation in True Height (σ_z) (feet)
700	34	111	116
500	67	144	159
300	119	219	250
200	161	315	354
100	229	418	477
50	291	630	694
25	355	1257	1306
10	456	3140	3173

* 3 mb up to and including 200 mb, 2 mb at 100 mb, and 1.5 mb above.

VI. CONCLUSION

Until such time as additional tests or studies indicate the need for revision, the accuracies discussed in this report should be useful in assessing the validity of plotted upper air data. For example, in analyzing the 500-mb chart, the plotted height data should be within about 70 feet of the actual height. An apparent error of 140 feet or more should be examined carefully for mistakes in plotting or coding. Also, the height of the base of an inversion (or of the 0°C isotherm) plotted near the 300-mb pressure level should be within 250 feet of the computed height, and only rarely would it be more than 500 feet in error.

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